

TETHER APPLICATIONS FOR SPACE STATION

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What I will be discussing with you this afternoon are a subset of the results from a study performed by Martin-Marietta Aerospace for Marshall Space Flight Center under the technical guidance of Georg von Tiesenhausen and Jim Harrison. During his earlier talk, Georg has already touched on some of the subjects that I will be talking about this afternoon.

We have looked at a wide variety of Space Station applications for tethers. Many of those will affect the operation of the Station itself while others are in the category of research or scientific platforms. My co-speaker will focus on the latter of these. I would like to discuss what we believe is one of the most promising potential applications that could increase the overall efficiency of the Space Transportation System in supporting the Space Station.

One of the most expensive aspects of operating the Space Station will be the continuing Shuttle traffic to transport logistic supplies and payloads to the Space Station. We must pay the freight bill for getting the Orbiter and its payload up into orbit, and then we pay the bill again when it comes back. If we can find a means to use tethers to improve the efficiency of that transport operation, it will increase the operating efficiency of the system and reduce the overall costs of the Space Station. The concept we have studied consists of using a tether to lower the Shuttle from the Space Station. This results in a transfer of angular momentum and energy from the orbiter to the Space Station. Our study has delved into the consequences of this transfer and how beneficial use can be made of it.

Please keep in mind that, if we have scavenged angular momentum from the tether de-orbiting of the Shuttle, we must then be able to beneficially use that angular momentum. I'd like to change the old saying "You can't have your cake and eat it, too" to a little different version - "Unless you can eat your cake, you really haven't had it." The point here is that, if we do not have a beneficial way to use this angular

momentum we have scavenged, we will quickly choke on it, because the altitude of the Space Station has been boosted up to where it becomes impractical for the follow-on missions to reach it.

In our study we have considered two alternative ways of accomplishing this required angular momentum balance. On my first slide (Figure 4) please direct your attention to the left side of the screen. Here I have shown one of our alternative approaches. Note the balance beam at the bottom to indicate we are balancing the Shuttle tether de-orbit against a tether launch assist for an orbital transfer vehicle. I'll show you in a few moments how we propose to implement that.

To review the concept here--let's start at the point where the STS comes up to rendezvous with the station. It operates in conjunction with the station for some period of time, and then does a tether-assisted de-orbit. At this point, there is a very significant increase in the altitude of the station. This is due to the angular momentum transferred to the Space Station from the Orbiter by the tether. We have used the altitude bounds of 250 nautical miles, which is a practical lower operating unit for the Space Station, and an upper limit of 310 nautical miles.

You can see that the Shuttle tether de-orbit gives a boost of a significant fraction of that range. It must then be followed in fairly close order with a corresponding tethered launch assist of the orbital transfer vehicle in an upward direction which, in turn, will drop the altitude of the station back down to a more reasonable operating range in preparation for the next Shuttle rendezvous mission.

For this process to continue, the downward and upward tether assisted launches must alternate in coordinated pairs to keep the angular momentum of the Space Station in balance.

Now, in contrast, look at the righthand side of the slide where the Shuttle de-orbit is balanced against an electrodynamic tether for power generation. Here there is a significantly more flexible capability to

achieve balance. What I have indicated here is a system where the angular momentum and energy scavenged from the Shuttle by the tether de-orbit is subsequently converted into electrical power by means of an electrodynamic tether power system.

The concept design is sized to operate at 25 kilowatts of power with the reserve capability of going up to 75 kilowatts. An interesting feature of this type of system is that they can be operated at a higher power level with the only penalty some loss of efficiency in converting the orbital mechanical energy into electrical power.

As a point of reference, if you operate the power tether at a 25-kilowatt conversion rate, you can maintain full duty cycle operation for approximately one month on the mechanical energy derived from one Shuttle de-orbit.

At the other extreme, if you want to lower the Space Station more rapidly and, presuming there is a way to use the power produced, a 75 kW conversion rate will return the Space Station to its original altitude in about a week. I'll discuss this in more detail a little later.

To reiterate, this second momentum balance concept is much more controllable in that the rate of converting the angular momentum can be regulated and, if there is a need to be back down to a lower altitude by a certain time, it can be done. To illustrate our approach to implementing these concepts, my next slide (Figure 6) shows a line drawing of the same concept that Georg had shown you earlier in a more colorful artist's rendition. I want to point out the dual mode tether reel assembly that can perform both the Shuttle de-orbit and the OTV launch assist. It is centrally located on the Space Station and incorporates the tether tension alignment systems at both the upper and the lower ends of the Space Station.

Here on the next slide (Figure 9) you see the Shuttle attached at the lower end. In this scenario, the Shuttle would have delivered an orbital transfer vehicle payload intended for a subsequent delivery

mission to geosynchronous orbit. That OTV payload has been transferred up to the assembly area on the upper end of the Space Station. The next step is for the Orbiter to separate from the station. It is then deployed downward on the tether to a length of 65 kilometers.

One of the interesting aspects of this de-orbit process is that the amount of propellant that is required for the Orbiter to re-enter is significantly reduced.

For a time, we were stymied as to how to take advantage of this. It can't be offloaded from the Orbiter until after you are down at that tether release altitude because, if the tether operation went awry somehow, the Orbiter would be stranded, and would have to come back to the station for propellant resupply before completing the re-entry.

As a solution we developed a concept to incorporate propellant scavenging tanks into the tether attach fixture that interfaces with the Orbiter. Now, as you lower the Orbiter down on the tether, these tanks are connected with the propellant storage system of the Orbiter. As the Orbiter is lowered and the propellant becomes excess to need, it is transferred from the Orbiter into the tether system scavenge tanks. At the full 65 km length, 6500 pounds of propellant will have been transferred. After separation, this scavenged propellant is retrieved by the tether. I will elaborate more later on how that adds up as savings.

Shown here on the next slide (Figure 10) is the other operation at the upper end of the station. Subsequent to the Shuttle de-orbit, a similar tether deployment of the OTV stack is performed from the upper end of the Space Station using the same tether deployment system. We examined the design requirements for commonality for the Orbiter and OTV deployments, and found that, if the orbital transfer vehicle were deployed out to a tether length of 150 kilometers, it would develop equivalent tensions in the tether to those resulting from the Orbiter at

65 km. This means we could use a common design for the tether and the deployer reel drive system. The OTV launch assist does require more storage of tether on the reel. It looks feasible to design one system that can perform both of these deployment operations.

My next slide (Figure 12) is similar to one shown earlier by Georg. It shows the benefits that accrue over a decade of operations. This analysis is based on Space Station mission model revision 7. The vertical scale is in terms of reduced requirements to transport propellant to the Space Station.

I first direct your attention to the lowest set of bars coded with a double crosshatch. This represents the Space Station saving in drag makeup propellant. This orbit maintenance function is accomplished by the Shuttle de-orbit operations, therefore, this stationkeeping propellant is no longer required. Note the change as we go into the later years of the decade. This is due to the reduced atmospheric drag during the quiet years of the solar cycle. The early years of the Space Station will be the ones with the most demand for drag makeup propellant.

The next element of transport saving is represented by the single crosshatch which stands for the propellant scavenged from the Shuttle. This is plotted at the upper end of the vertical bars. This shows the amount of propellant that we have scavenged from the Shuttle and retrieved for use in spacecraft such as the orbital maneuvering vehicle.

Note that the benefit here is very limited during the early years of the decade. This limit holds until the space-based orbital transfer vehicle comes into operation in 1995.

Until that time, the amount of Shuttle tether de-orbits that can be utilized is that corresponding to the relatively small amount required for Space Station drag makeup. Here again I want to emphasize that you must have a way to beneficially utilize the scavenged angular momentum before you can take full advantage of the process. Notice that out here in the later years, when the orbital transfer vehicle comes into full

operation, that we have these much more significant amounts of OMS propellant because we can now use a full length tether de-orbit on more of the Shuttle missions.

A third major element of benefit is the reduced amount of cryogenic propellant for the OTV missions. This is coded as the clear portion of the bars. This reduction is due to the launch assist given the OTV by the tether system.

So we have these three major elements of propellant transport saving. The propellant that is no longer required at the Space Station to do the drag makeup, the reduced amount of cryogenic propellant for the orbital transfer vehicle, and the Orbiter propellant that is scavenged during the Shuttle de-orbit.

Starting with my next slide (Figure 14), I'd like to take you through a similar kind of benefits analysis for the electrodynamic tether and show you how that case differs. The system design constraints are listed. We used 25 kW as our design requirement for the electrodynamic power tether. It was designed for a system conversion efficiency of 80 percent. In order to achieve this efficiency, no more than 5 percent of the system power could be dissipated in the tether as heating.

If the power level is increased up to 75 kilowatts, this efficiency drops to 70 percent, as I will show you later.

We designed the system so that the tether angle from vertical is always less than one-tenth of a radian, or about six degrees, even when operated at the 75 kW reserve power level. The reason we did this is to prevent the electrodynamic drag on the power tether from tilting the station when it's drawing maximum power. We wanted to keep that angle small enough so that one of our tension alignment stages could be used to keep the station vertical.

The assumptions used for the Space Station itself are a mass of 250,000 kilograms in a 500-kilometer orbit. It now looks as if the station will grow to a larger mass than that in the more mature phases. That will tend to further improve the overall arithmetic on this system.

We have used an end mass of 500 kilograms to support the required subsystems at the end of the tether.

On my next slide (Figure 16) is shown a plot of the relationship between the mechanical energy derived from a tether de-orbit of a Shuttle and the conversion of this energy into electrical power by an electrodynamic power tether. A tether de-orbit of Shuttle causes an 80 km boost in altitude for the Space Station.

On the vertical axis is shown the kilowatt hours per kilometer of orbit altitude. And, as you can see, over this range, it ranges from about 297 kilowatt hours per kilometer of altitude down to about 288. Although stated in electrical units, this is actually mechanical energy content of the orbiting Space Station. If you boost the orbit altitude of the Space Station by 80 km, that results in 21,700 kilowatt hours of mechanical energy that have been transferred into the orbit. I submit to you - that's a rather impressive amount of energy.

Now referring to the table in the upper right of the slide, we can see what happens when we convert that mechanical energy back into electrical power. Note the two columns on the right under the two power levels of 25 kW and 75 kW. The next numbers down give the corresponding system efficiencies in converting that mechanical energy into electrical energy. As I stated earlier, the efficiency is 80 percent at 25 kW and 70 percent at 75 kW. Next you see the number for the orbit altitude loss per day. The bottom entries show that at the 25-kilowatt power level, the system can sustain operations for 29 days and for 8.4 days at 75 kilowatts.

The next slide (Figure 17) is an accrued benefits plot similar to the one shown earlier. The corresponding values look a little bit

different here and requires some additional explanation. Again, I have shown the scavenged Orbiter propellant savings. Unfortunately, I changed the marking code and here the Orbiter propellant is shown as the clear bar, and the cross-hatched one is the drag makeup propellant saved. These are the elements making up the bars that are on the left.

Note the significantly increased transport benefits during the early years of Space Station operation. This is because with this concept there is not a requirement to pair a Shuttle de-orbit with an OTV launch assist. The maximum amount of Shuttle propellant can be scavenged from the beginning of Space Station operations.

But now we have this new commodity that came into being with this concept, and that is the amount of electrical power made available on the Space Station. I used the evaluation of a hundred dollars per kilowatt hour on orbit. The accrued numbers of kilowatt hours of electrical energy per year are identified in the shaded bars on the right. The dollar value numbers are at that hundred dollars per kilowatt hour.

The point of this plot, in contrast to the earlier one, is that it does not have the step change due to the advent of the space-based OTV in 1995. It means, if we had an electrodynamic power tether, we could start beneficially utilizing the full available amount of scavenged angular momentum right from the beginning. We could begin as soon as the Space Station is in operation with the capability to sustain such a tether system.

The conclusions that I had made were very close to the ones that Georg had listed. In order to keep on schedule I will skip that slide. My presentation had originally been planned for a longer time so there are some additional slides in the package which I have left there for information.

Thank you for your attention.

TETHER APPLICATIONS
FOR
SPACE STATION

APPLICATIONS OF TETHERS IN SPACE WORKSHOP

VENICE, ITALY

OCT 15-17, 1985

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PHASE I STUDY RECAP

- o STUDY COMPLETED JULY 84
- o INITIAL SURVEY OF 26 + CONCEPTS
- o CONCEPTS SELECTED FOR STUDY

CONCEPTS	TETHER LOCATION
A - TETHER DEORBIT OF SHUTTLE	SPACE STATION
C - TETHERED PLATFORM	SPACE STATION
D - TETHER MEDIATED RENDEZVOUS (OMV WITH OTV)	SPACE STATION
E - ELECTRODYNAMIC TETHER (DUAL MODE FOR ENERGY STORAGE	SPACE STATION

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INSIGHTS GAINED - CONCEPT REVISIONS MADE

ANGULAR MOMENTUM BALANCE

- THE IMPRESSIVE AMOUNTS OF ANGULAR MOMENTUM MADE AVAILABLE BY TETHER DEORBIT OF SHUTTLE REQUIRES CORRELATED CONCEPTS TO USE IT BENEFICIALLY

REVISIONS

- CONCEPT F - TETHER LAUNCH ASSIST TO OTV MISSIONS
- CONCEPT E2- ELECTRODYNAMIC TETHER AUXILIARY POWER SYSTEM

OMS PROPELLANT SCAVENGING

- AMOUNT OF SURPLUS OMS PROPELLANT (6500 LBS) RESULTING FROM TETHER DEORBIT OF SHUTTLE
- OPERATIONAL SAFETY CONSTRAINTS ON OMS OFF-LOAD PRIOR TO TETHER DEORBIT

REVISION

- CONCEPT A2- TETHER DEORBIT OF SHUTTLE WITH OMS SCAVENGING

FUNCTIONAL PAIRING OF CONCEPTS

- ANGULAR MOMENTUM BALANCE PAIRING OF CORRELATED CONCEPTS
- COMMONALITY OF REQUIREMENTS (A2 AND F)

REVISION

- DUAL MODE DEPLOYER SYSTEM (SHUTTLE DEORBIT, OTV LAUNCH)

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PHASE II STUDY CONCEPTS BASELINE

SPACE STATION BASED TETHER

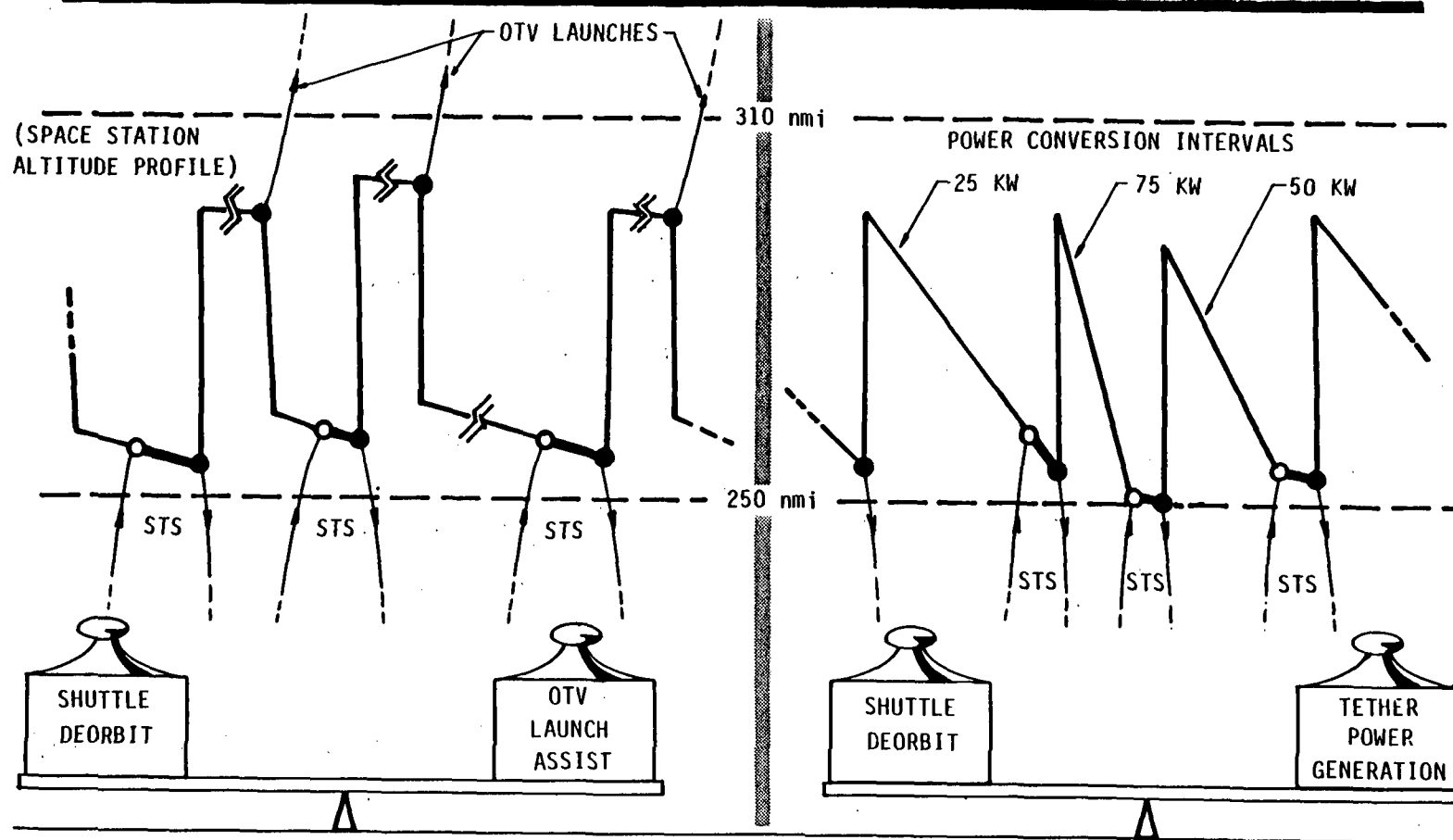
- A2 - TETHER DEORBIT OF SHUTTLE WITH
OMS PROPELLANT SCAVENGING (REVISION)
- F - TETHER LAUNCH ASSIST TO OTV (NEW)

BASIS FOR
DUAL MODE
DEPLOYER SYSTEM
ON SPACE STATION

- C - TETHERED PLATFORM (SAME)
- D - TETHER MEDIATED RENDEZVOUS OF OMV WITH OTV (SAME)
- E2 - ELECTRODYNAMIC TETHER FOR AUXILIARY POWER SYSTEM (NEW)

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ALTERNATIVE APPROACHES TO ANGULAR MOMENTUM BALANCE



- = STS RENDEZVOUS WITH SS
- = TETHER DEORBIT/LAUNCH ASSIST

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CONCEPT DESCRIPTIONS

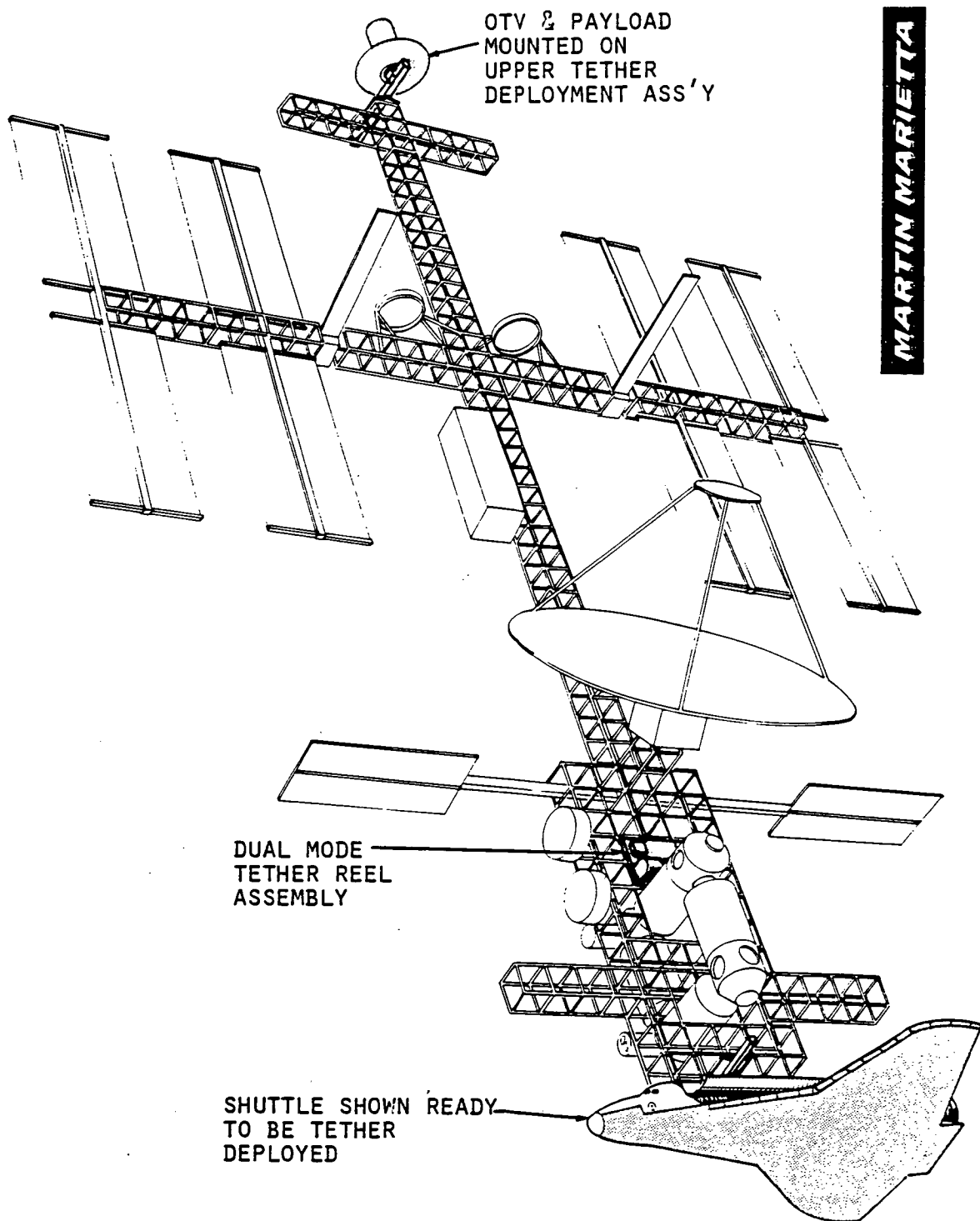
PAIRED CONCEPTS

A2 - TETHER DEORBIT OF SHUTTLE

F - TETHER LAUNCH ASSIST OF OTV

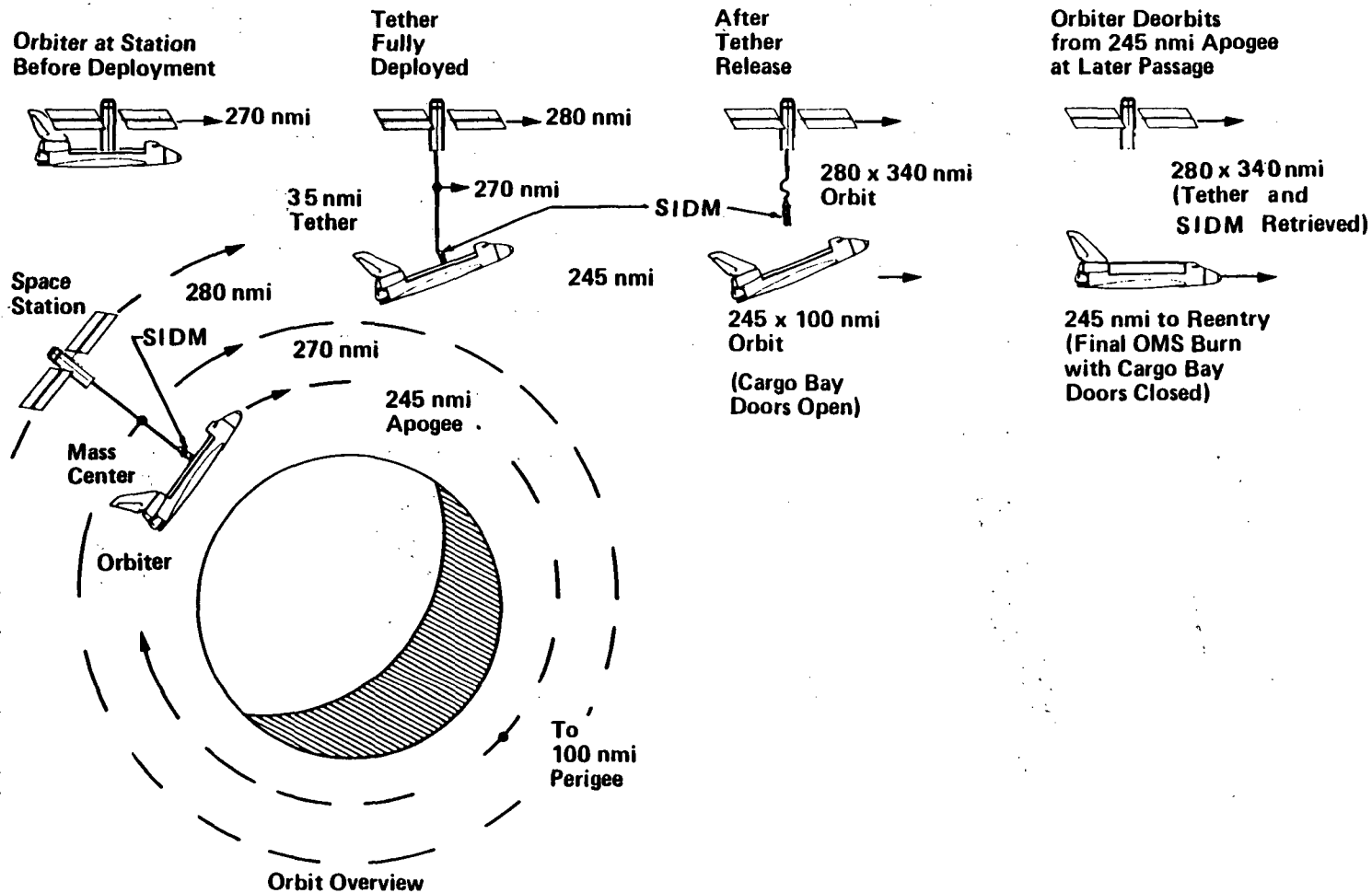
DUAL MODE SPACE STATION DEPLOYER SYSTEM

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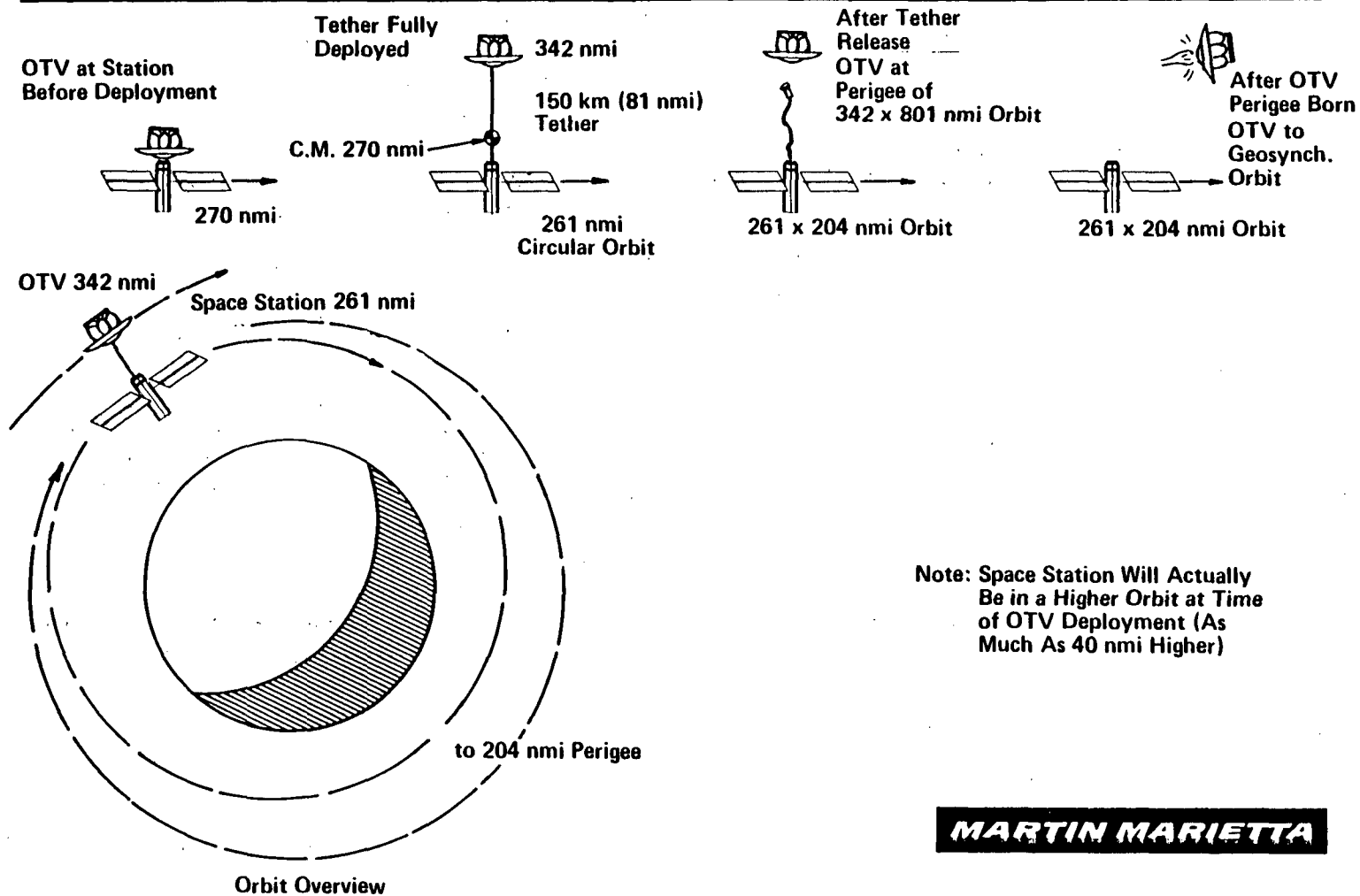


DUAL MODE TETHER DEPLOYMENT SYSTEM INSTALLED ON SPACE STATION

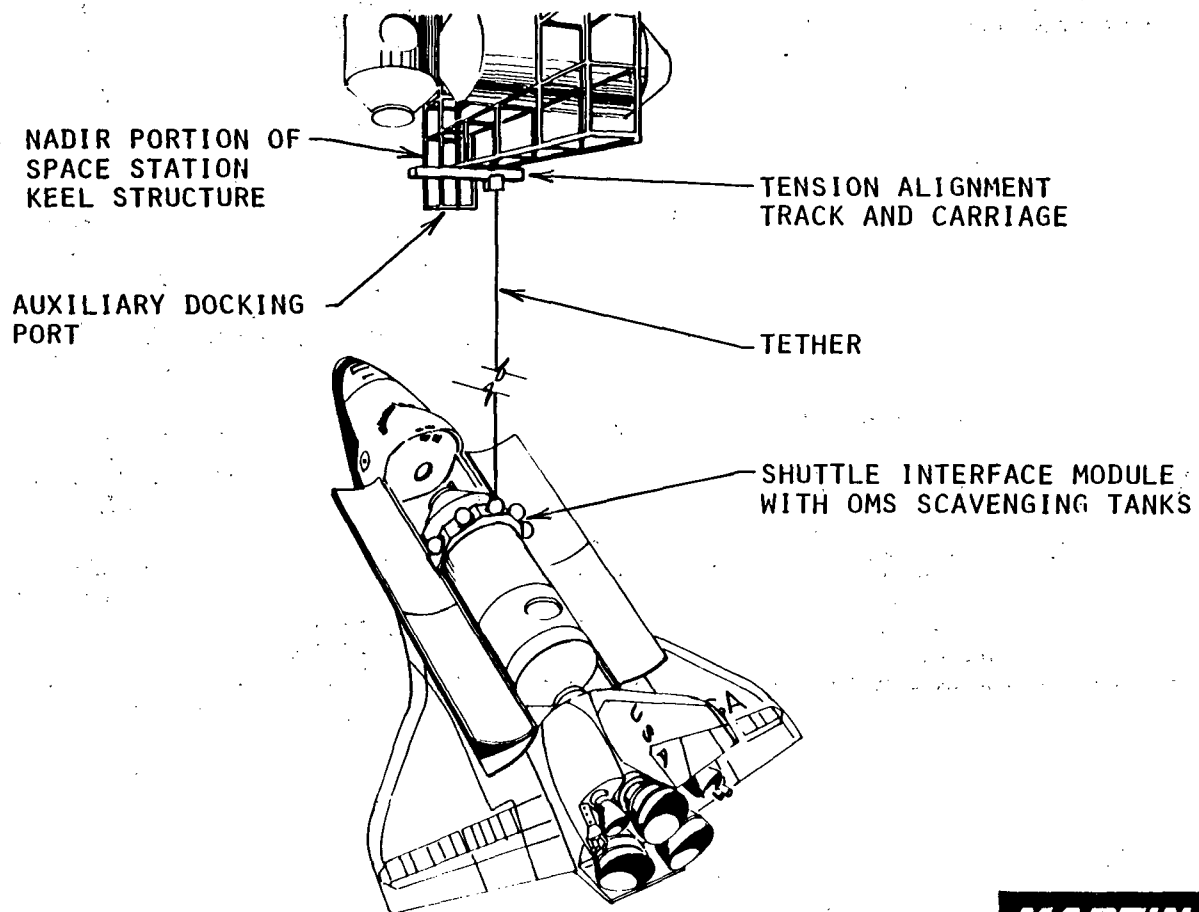
Shuttle Deorbit Sequence/Space Station Response



TETHERED OTV LAUNCH SEQUENCE/SPACE STATION RESPONSE

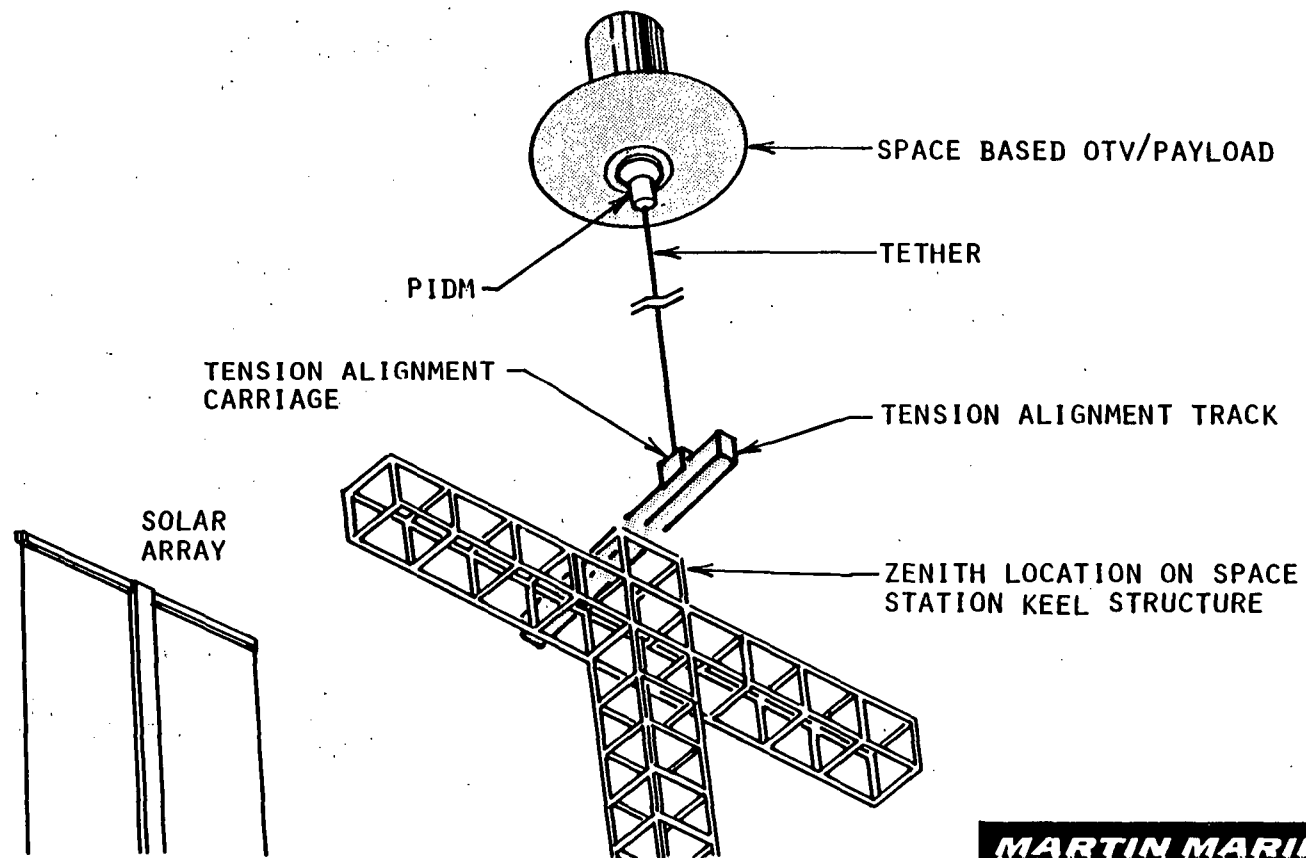


TETHER DEORBIT OF SHUTTLE



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OTV TETHER LAUNCH ASSIST



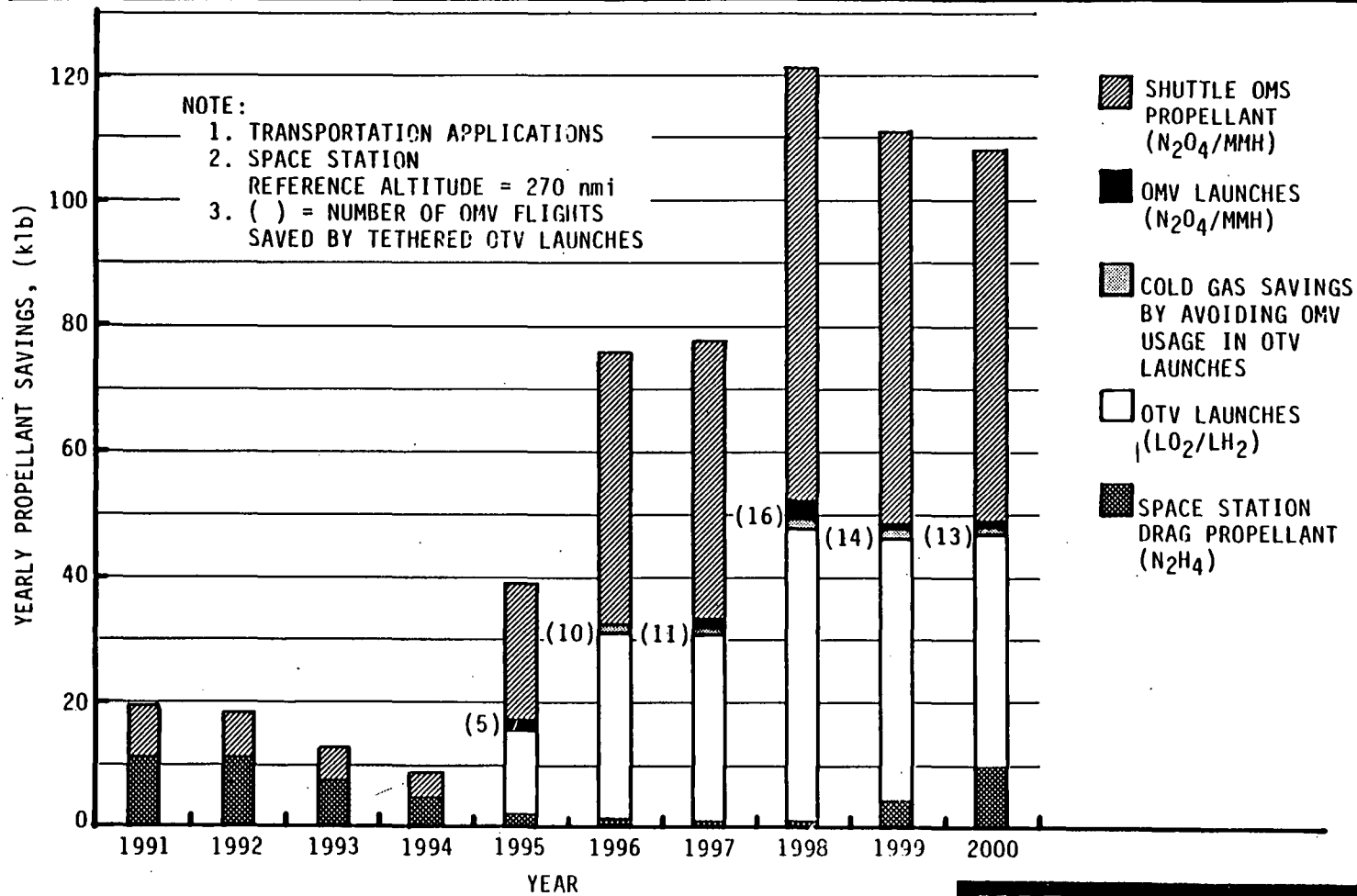
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TECHNICAL ISSUES A2 AND F

- TETHER
 - DESIGN FOR ACCEPTABLE RECOIL
 - MULTIPLE REUSE DURABILITY
 - DEBRIS COLLISION HAZARD
- ENERGY MANAGEMENT
 - GENERATED BY DEPLOYMENT (A2/153kWh), F/366 kWh)
 - REQUIRED FOR RETRIEVAL (A2/11 kWh, F/29 kWh)
- SPACE STATION IMPACTS
 - INDUCED ACCELERATION LEVELS ($10^{-2}g$)
 - ORBIT PERTURBATIONS
 - STRUCTURAL STRESS
 - DEPLOYER SYSTEM LOCATION REQUIREMENTS
- OTV/TETHER INTERFACE
- OMS PROPELLANT SCAVENGING INTERFACE TO SHUTTLE

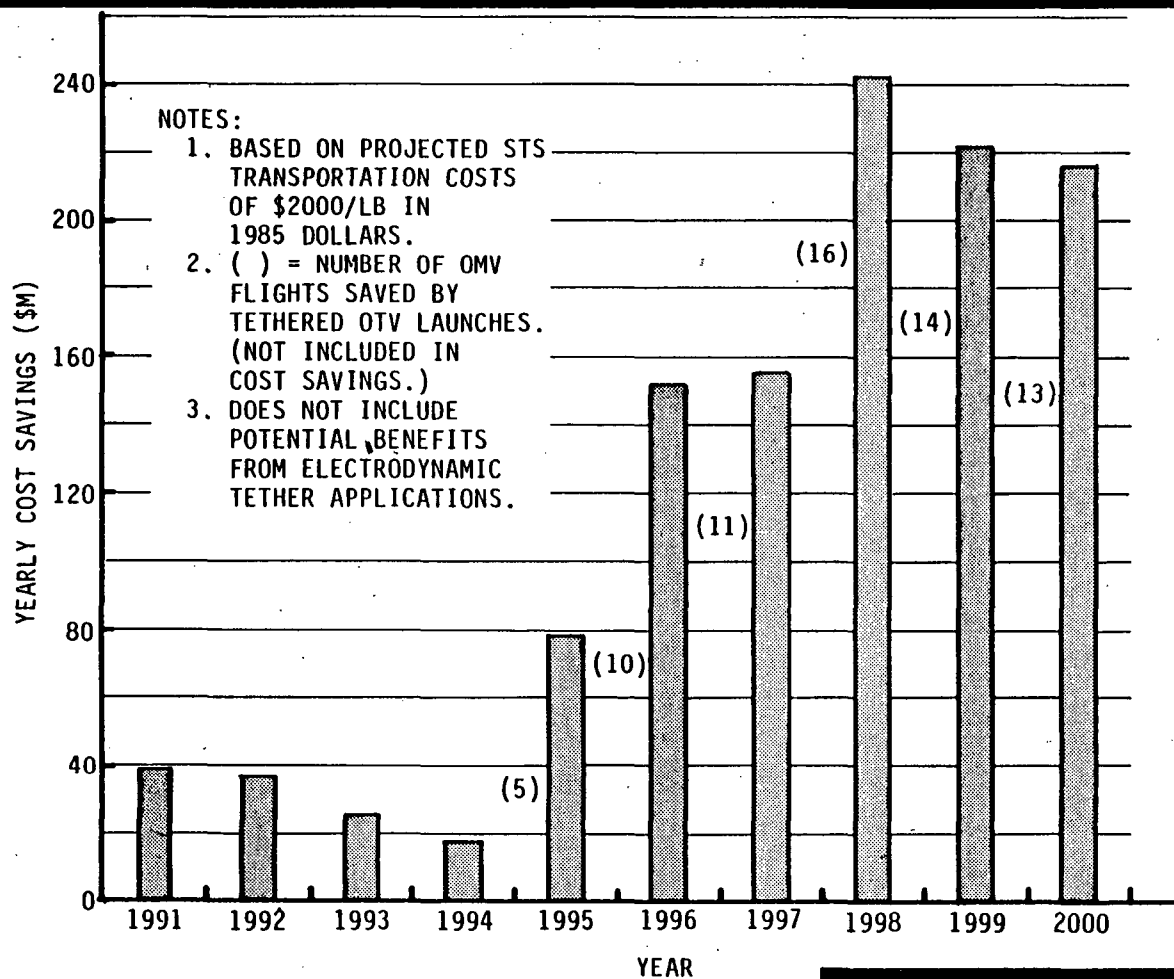
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POTENTIAL YEARLY BENEFITS FROM SPACE STATION TETHER OPERATIONS



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POTENTIAL COST SAVINGS FROM SPACE STATION TETHER OPERATIONS


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E2 - SYSTEM DESIGN REQUIREMENTS

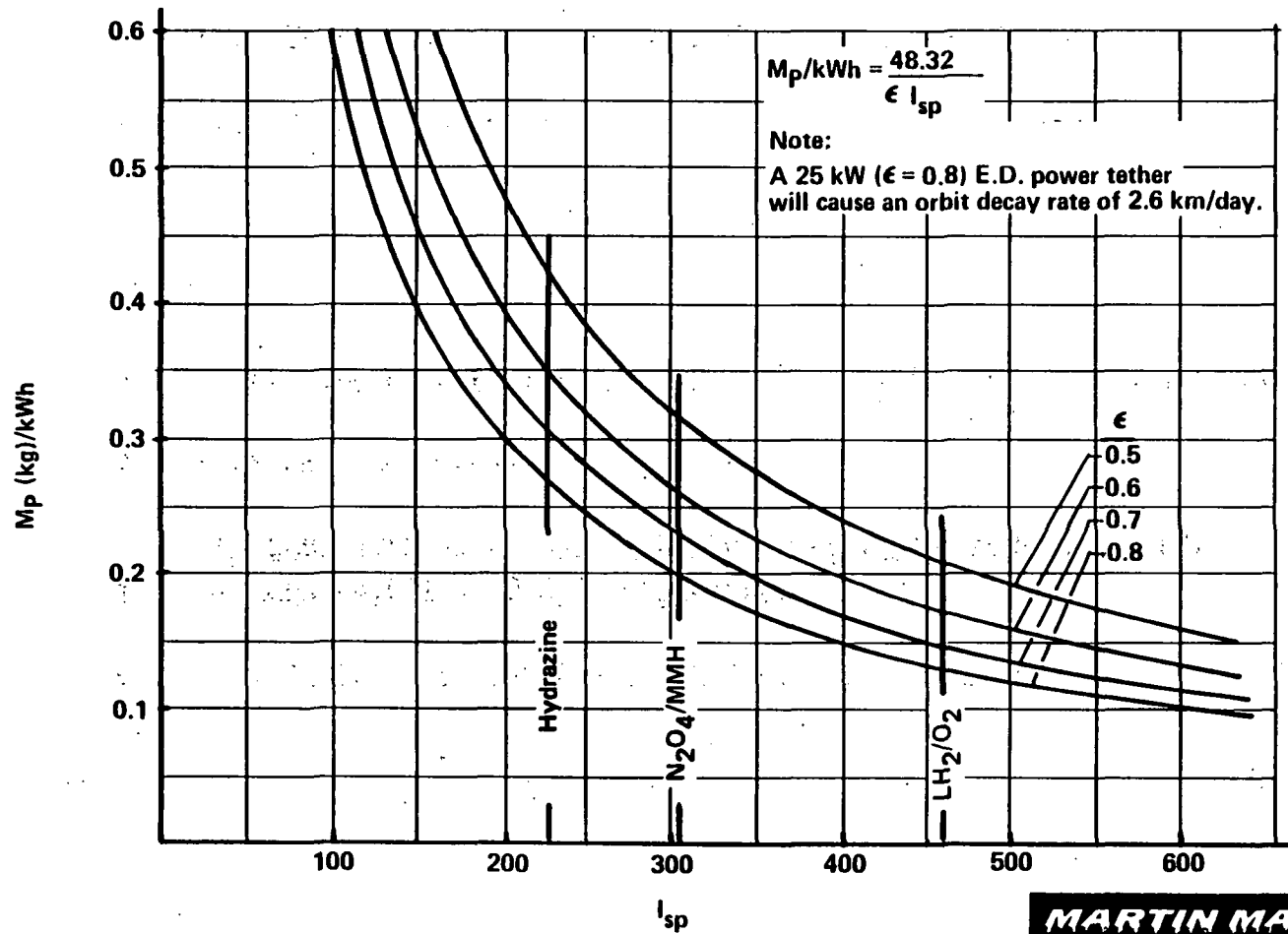
- DELIVER 25 kW TO SPACE STATION BUS-FULL DUTY CYCLE
- MAXIMUM PRACTICAL SYSTEM EFFICIENCY
(NO MORE THAN 5% OF SYSTEM POWER TO BE DISSIPATED IN TETHER)
- RESERVE LEVEL CAPABILITY OF 75 kW
- TETHER ANGLES LESS THAN 0.1R FROM LOCAL VERTICAL AT RESERVE POWER LEVEL

ASSUMPTIONS

- SPACE STATION MASS 250,000 KG. 500 KM ORBIT
- TETHER END MASS 500 KG
- ORBITAL ENERGY DERIVED FROM TETHER DEORBIT OF SHUTTLE

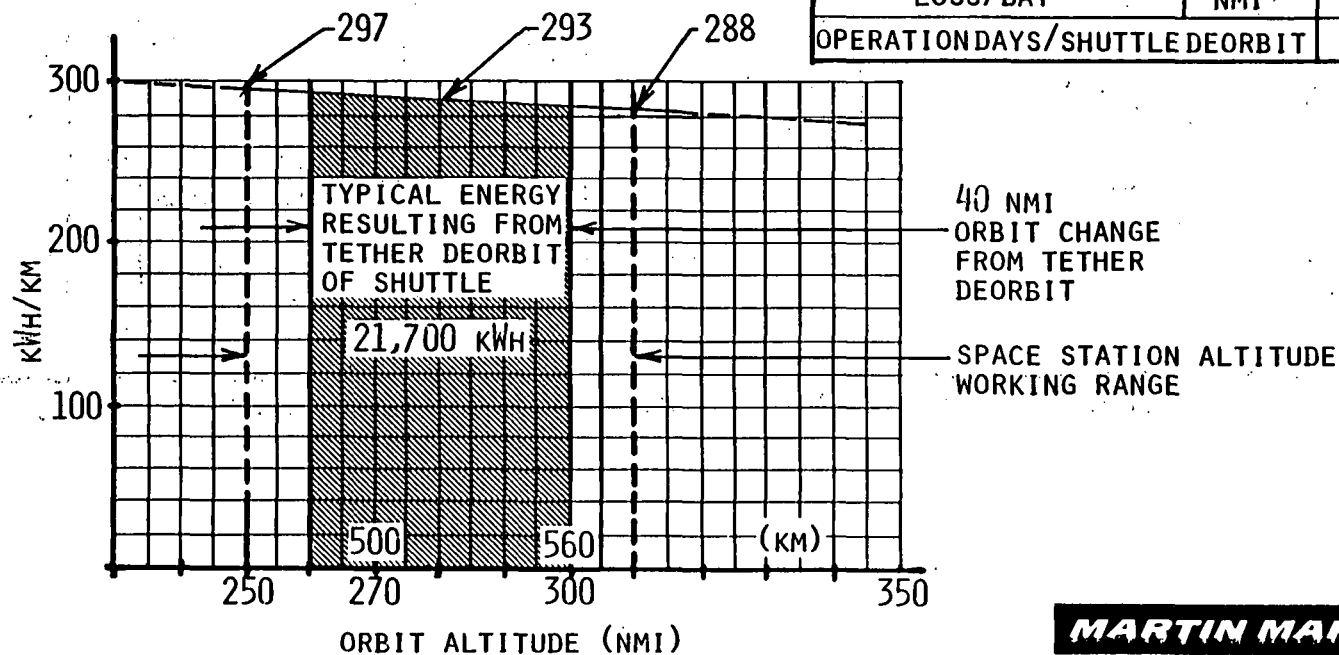
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REBOOST PROPELLANT REQUIREMENTS



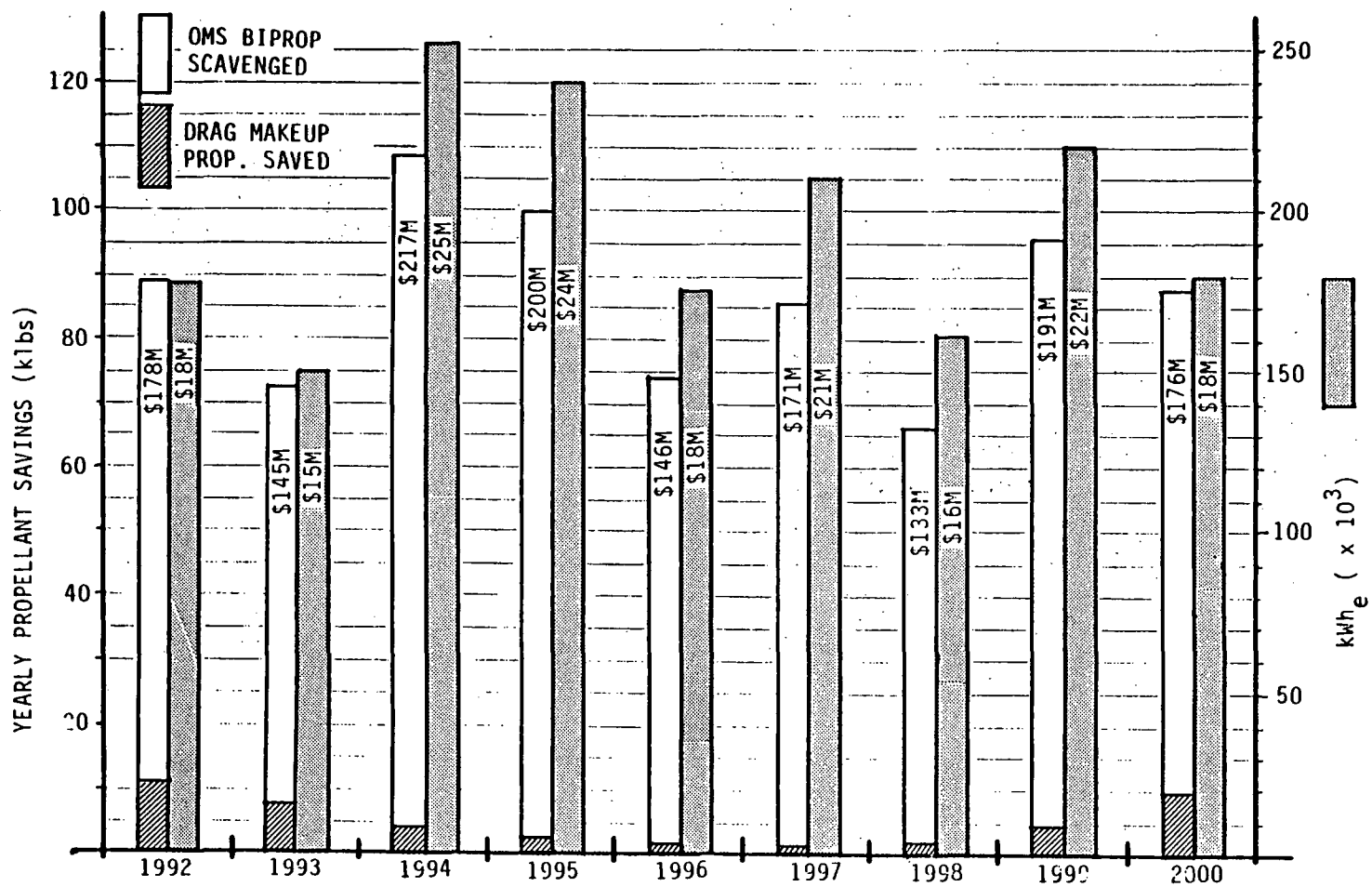
ELECTRODYNAMIC POWER TETHER ENERGY CONSIDERATIONS

ENERGY/ALTITUDE LOSS	KWH/KM	293 (AVG)	
	KWH/NMI	542 (AVG)	
TETHER POWER LEVEL (KW)		25	75
SYSTEM EFFICIENCY (%)		80	70
ENERGY CONVERTED/DAY (KWH)		750	2571
ORBIT ALTITUDE LOSS/DAY	KM	2.6	8.8
	NMI	1.4	4.8
OPERATION DAYS/SHUTTLE DEORBIT		29	8.4



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POTENTIAL BENEFITS - TETHER DEORBIT OF SHUTTLE / E.D. TETHER AUX. POWER SYSTEM



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ORIGINAL PAGE IS
OF POOR QUALITY

CONCLUSIONS AND RECOMMENDATIONS

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CONCLUSIONS

- TETHER TECHNOLOGY HAS THE POTENTIAL TO SIGNIFICANTLY INCREASE THE PERFORMANCE EFFICIENCY OF THE INTEGRATED SPACE TRANSPORTATION SYSTEMS
 - SHUTTLE (OMS SCAVENGING; INCREASED PERFORMANCE ENVELOPE)
 - SPACE STATION (ORBIT MAINTENANCE; AUXILIARY POWER)
 - OTV (REDUCED PROPELLANT; INCREASED PERFORMANCE)
 - OMV (INCREASED PERFORMANCE ENVELOPE)
- POTENTIAL COST AVOIDANCE OF \$250M + PER YEAR
- SURPLUS OF ANGULAR MOMENTUM AVAILABLE TO BE SCAVENGED FROM SHUTTLE. OTHER DEORBIT CANDIDATES AVAILABLE (WASTE PACKETS, E.T.'S)
- APPLICATION CONCEPTS ARE INTERACTIVE AND SHOULD BE CONSIDERED IN COMPLEMENTARY/COMPATIBLE SETS)
- ACCOMMODATION PROVISIONS MUST BE INCORPORATED INTO THE DESIGN OF ALL AFFECTED SYSTEMS
- OPERATIONAL IMPACTS ARE INHERENT AND MUST BE ACCEPTABLE TO AFFECTED SYSTEMS (ACCELERATION; ORBIT PERTURBATIONS)

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